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Philadelphia Roadway Study

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Research Triangle Park, NC

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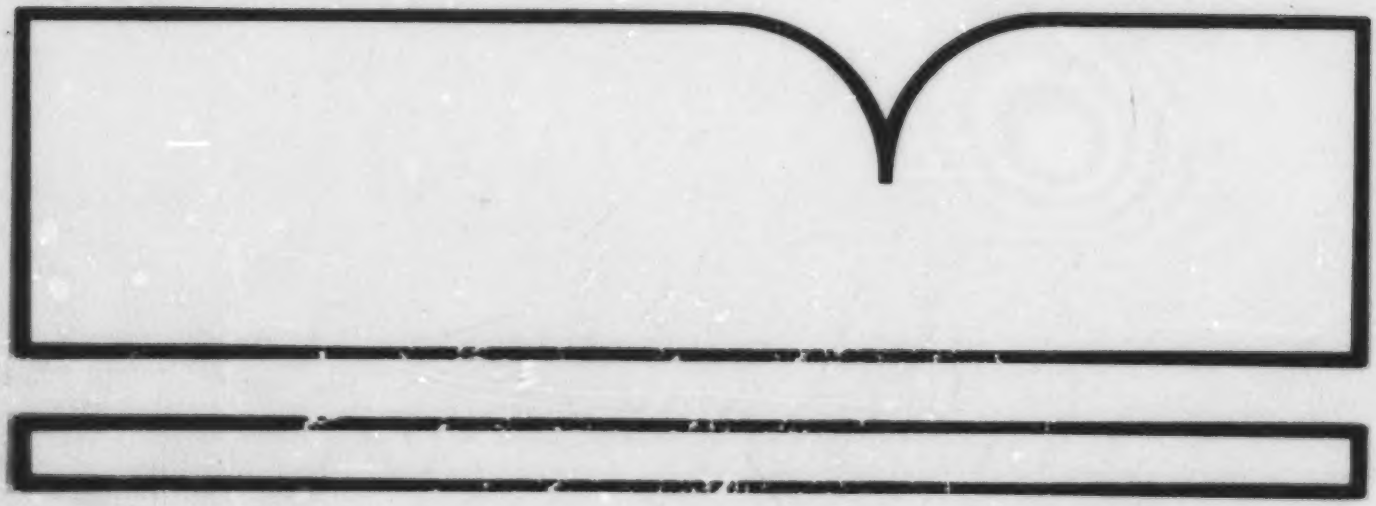

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August 1984

PHILADELPHIA ROADWAY STUDY

by

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16. ABSTRACT

The Philadelphia Roadway Study was conducted to determine the horizontal and vertical extinction profiles of particles generated by vehicles, including fine (0-2.5 μm), coarse (2.5-15 μm), and total (0-15 μm) size fractions in the area surrounding a major roadway. Particulate concentration profiles were characterized to a horizontal distance of 175 m downwind and to a height of 15 m above ground (at five and 25 m downwind) with the primary objective of estimating the influence of a nearby roadway on ambient particulate mass concentration levels. The dilution gradients for concentrations of fine, coarse, and total mass and fine lead particles at two m height are described empirically as a function of downwind distances from the highway using logarithmic equations. Wind speed had a substantial influence on the particulate mass concentration levels both upwind and downwind while the limited range of traffic densities, i.e., 2119-3906 vehicles/hour during the experiment, did not. Fine particulate mass at a height of 2 m at five m downwind was elevated 18% above background, coarse mass 45%, and fine lead 718%. Exponential equations relating concentration to the reciprocal of height and distance were fit to the data for both ground level and vertical concentration. Concentration isopleths were constructed to map suggested siting constraints.

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ABSTRACT

The development and implementation of a size-specific ambient particulate standard will require information on particle dispersion in the vicinity of localized sources such as major roadways to provide guidance in sampler siting. The Philadelphia Roadway Study was conducted to determine the horizontal and vertical extinction profiles of particles generated by vehicles, including fine (0-2.5 μm), coarse (2.5-15 μm), and total (0-15 μm) size fractions in the area surrounding a major roadway. Particulate concentration profiles were characterized to a horizontal distance of 175 m downwind and to a height of 15 m above ground (at five and 25 m downwind) with the primary objective of estimating the influence of a nearby roadway on ambient particulate mass concentration levels.

The dilution gradients for concentrations of fine, coarse, and total mass and fine lead particles at two m height are described empirically as a function of downwind distances from the highway using logarithmic equations. These equations, with correlation coefficients greater than 0.96 for all fractions, are based on purely statistical methods of investigating the relationship between concentration and distance and were not tested for distances less than five m or greater than 175 m.

Wind speed had a substantial influence on the particulate mass concentration levels both upwind and downwind while the limited range of traffic densities, i.e., 2119-3906 vehicles/hour during the experiment, did not. The magnitude of the lead component of the collected particulate mass agrees well with estimates based on tailpipe emission rates. Fine particulate mass at a height of two m at five m downwind was elevated 18% above background, coarse mass 45%, and fine lead 718%.

Exponential equations relating concentration to the reciprocal of height and distance were fit to the data for both ground level and vertical concentrations. These equations resemble a line source exponential dilution equation used to describe dilution of inert gases downwind of a Los Angeles freeway.[1] The exponents in the present study were fitted by least squares regression and are defined as the vertical gradient coefficients. A factor involving the reciprocal of the height raised to the power of an exponent estimated by least squares, was used to modify the ground level equations to empirically describe mass concentrations at any point downwind in both vertical and horizontal directions. Using two dimensional least square regression techniques, concentration isopleths were constructed to map regions of excess particulate mass and lead downwind of the roadway.

This report covers a period from March, 1982 to May, 1982 and work was completed as of May, 1982.

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FOREWORD

Measurement and monitoring research efforts are designed to anticipate potential environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Environmental Monitoring Systems Laboratory, Research Triangle Park, North Carolina has responsibility for: assessment of environmental monitoring technology and systems; implementation of agency-wide quality assurance programs for air pollution measurement systems; and supplying technical support to other groups in the Agency, including the Office of Air and Radiation, the Office of Toxic Substances, and the Office of Solid Waste.

The results of this study provide guidance to those persons responsible for establishing long term size-specific particulate monitoring stations in areas surrounding major roadways. As a result of the study, the distance from roadways required for siting particulate samplers for various monitoring objectives can be more precisely determined.

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SECTION 1

INTRODUCTION

The May 10, 1979 Federal Register included an appendix entitled "Probe Siting Criteria for Ambient Air Quality Monitoring" which addresses the siting of Total Suspended Particulate (TSP) Hi-volume Samplers near roadways[2]. Studies have shown that TSP levels decrease with increasing height and horizontal distance that the monitor is placed away from the roadway[3]. For ambient 24-hour surveillance monitoring, a sampler set too close to any localized source such as a heavily traveled roadway would overestimate the level of TSP for the general surrounding area.

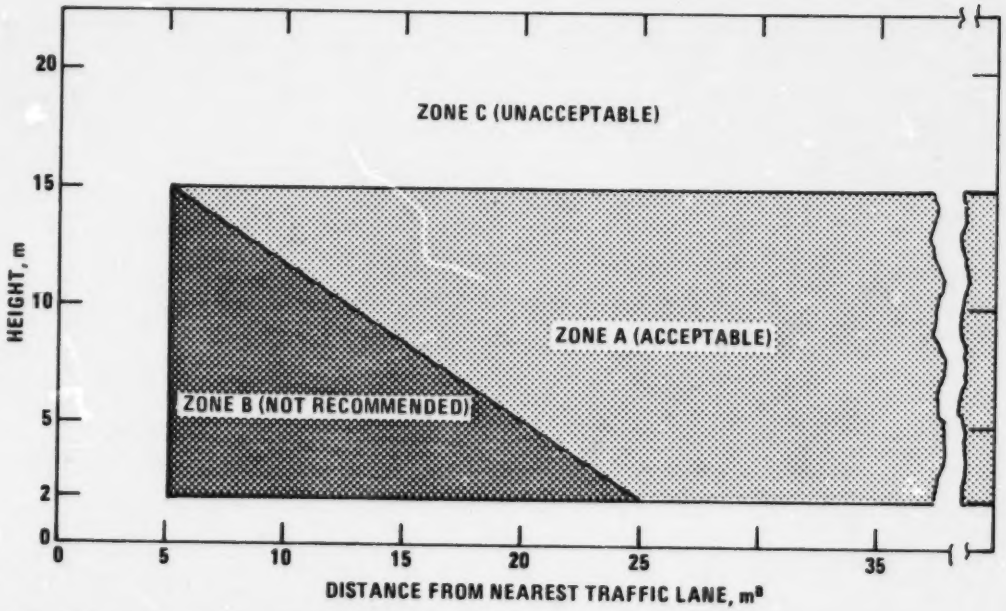
Figure 1 is taken from the Federal Register and shows the existing guidelines for siting TSP samplers near roadways. The figure was developed using data from a number of studies which demonstrate that TSP mass levels decrease with increasing height and horizontal distances away from a roadway. Pace[3] showed that a linear relationship between sampler height and distance from roadways defines a zone where the roadway emissions of traffic greater than 3,000 vehicles per day is diminished. Figure 1 reflects the zoning with Zone A defining the area acceptable for TSP sampling not directly influenced by the roadway emissions plume. Zone B defines the area, in terms of vertical and horizontal distances, where TSP sampling would be biased by the plume coming from the roadway emissions. Sampling is not permitted in Zone C since the area above 15 m does not represent the atmosphere where the majority of the human activity occurs.

The development and implementation of a size-specific ambient particulate standard instead of the current Total Suspended Particulate standard will require additional information on dispersion of the various size fractions of particles in the area surrounding a major roadway. This information will be used to support a revision of the criteria shown in Figure 1.

Since the rate of deposition and vertical diffusion depend upon particle size, the criteria shown in Figure 1 cannot be assumed to apply to both the larger coarse (2.5 to 10 or 15 μm) and the smaller fine (<2.5 μm) fractions. Smaller particles are assumed to deposit from the atmosphere more slowly than the larger ones, with the submicron size particles behaving nearly as a gas. With no reactions, pollutant gases tend to decrease in concentration away from a source because of dilution. Suspended particles are reduced in concentration by both dilution and deposition.

The primary objective of this study was to collect particulate mass concentration data to define vertical and horizontal distances from roadways

required for inhalable particulate (IP) monitor siting. Secondary objectives were to compare the particulate mass measurements to a simple model which considers both dilution and settling of particulate matter and to determine if the siting criteria for inhalable particulate matter (<15 μm) applies to lead (Pb) measurements made with an IP sampler.



[a]APPLIES WHERE AVERAGE DAILY TRAFFIC EXCEEDS 3000

Figure 1. Acceptable zones for siting TSP monitors.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Significant differences at the 95% confidence level were found to exist between downwind (including roadway) and upwind background mass concentrations of fine, coarse, and total particulate matter. Significant differences at the 95% confidence level also were found for the lead component of the mass fractions.

Within wind speed and traffic density boundaries of the study, the downwind mass gradients in the vertical and horizontal directions were predictable from an empirical relationship. Therefore, zoning graphs for use in developing siting constraints were obtainable for the mass and lead fractions. The bromine/ lead ratio was found to be consistant with other studies indicating that the increased lead mass levels were generated from the roadway. The criteria for siting TSP samplers (presently in the Federal Register) cannot be used for siting IP samplers since the constricted area is not bounded by a straight line as given in the TSP criteria. The area is bound by an exponential function with respect to height and distance. The downwind mass and lead concentration profiles for each size fraction measured are similar in shape but extinction rates vary considerably for the different fractions measured.

The particulate mass settling rate (deposition) downwind to a distance of 175 m is not significant. The downwind horizontal decrease in particulate concentration at a height of two m is due mostly to the upward diffusion of the particles. Only 1.2% of the fine mass is lost between five m and 25 m downwind at a height up to 15 m. The coarse mass decreased 9.7% at the same height and over the same distance. One cannot assume that correct siting can be accomplished by placing the sampler at a greater height, since the plume rises with distance downwind. The downwind dilution rate of lead associated with the fine fraction is different from that of the fine or coarse mass fraction. Most of the lead remains below a height of seven m vertically, and is significantly above zero at a distance of 175 m downwind.

It was possible to empirically derive two dimensional exponential equations describing dilution of mass and lead content in both the horizontal and vertical directions downwind which account for greater than 90% of the variability in the data. The equations are of the form used to describe dilution of an inert gas. However, the exponents in the fitted equations are not in agreement with the values found previously. The dilution rate is highly influenced by the difference in concentration upwind and that directly downwind of the source.

This study considered downwind particulate mass measurements at times only when the wind was perpendicular to the roadway and greater than two mph and less than 18 mph. Other cases should be tested when the wind is parallel to the roadway and less than two mph. Vertical measurements at the upwind background site would be helpful to verify that no vertical gradient exists. The empirical equations developed from the study should be tested for validity at higher and lower levels of mass obtained at locations where greater traffic density variations occur.

SECTION 3

EXPERIMENTAL PROCEDURES

APPROACH

The approach was to collect the fine and coarse particulate mass fractions at one point upwind, one point in the center, and nine points directly downwind of a major roadway when the wind direction was within a 90 degree sector centered about the perpendicular to the road. Horizontal distances are referenced from the edges of the 60 m wide roadway unless otherwise noted. Likewise, vertical distances are referenced from ground level. These data could then be used to construct concentration isopleths. The upwind sampling site was used for estimating the background concentrations. A sampling site was located in the roadway median on the perpendicular to verify the maximum concentrations extrapolated from the roadside measurements. Sierra Model 244E Dichotomous Samplers with 15 μm inlets were used for collecting the fine and coarse fractions on 37 mm teflon filters. The dichotomous samplers were operated in accordance with procedures of the Inhalable Particulate Network (IPN)[4]. The particle separation characteristics of the sampler are based on aerodynamic particle size which transforms the actual diameter to the equivalent diameter of a unit density sphere having the same settling velocity as the particle in question of whatever shape and density. All particle sizes referred to in the report are aerodynamic diameter. Sampling was initially performed (Phase I) at ground level two m height above the roadway to determine at what point downwind the concentration had been reduced by upwind diffusion and particle deposition to approximately the background level. Sampling in the vertical direction was then conducted using two towers -- one located at roadside five m downwind, and the other approximately half-way downwind from roadside to the point at which the roadway particulate mass concentrations had dropped to within 10% of background level. The half-way point was found to be approximately 25 m downwind.

Meteorological measurements for wind speed, wind direction, temperature and humidity were made from a 15 m height at the monitoring site located five m downwind of the roadway. A Climatronics electronic weather station was used to acquire the data on strip chart recordings.

Based on historical meteorological data for the area, particle sampling was initiated in March, 1982, to obtain the downwind particle concentration gradient under wind direction conditions that were expected to be primarily perpendicular within ±45° of the roadway. In order to minimize variations in wind speed and direction during particle sampling, sampling periods of "acceptable" meteorology were limited to a 14 hour (7:00 AM -9:00 PM) daytime sampling period. With this schedule the early morning inversions, wind instability and the night time low traffic count were eliminated.

Based on data from an earlier study[1], sampling was only conducted when wind speeds were above two mph and wind directions within ±45° of the freeway perpendicular. Wind speeds below two mph do not provide adequate transport to define a profile[1]. Wind directions perpendicular within ±45° were expected to provide ratios of downwind to upwind concentrations exceeding at least a factor of two.

A Climatronics Wind Controller (Model WMIII - PN100864) activated by wind speed and direction sensors limited sampling to periods when parameters were within preset specifications. The statistical study design recommended at least 10 valid sample runs for the horizontal configuration and 10 for the vertical configuration. A sample run was required to last for at least four hours in order to have adequate mass collection on each dichotomous sample filter.

The number of vehicles operating on the roadway during the study was very important. Any large fluctuations in traffic count would affect the particle concentration levels (and hence the isopleths) around the study site. Mechanical car counters were used to obtain real time hourly traffic counts. Daily traffic flows ranged from 2119 to 3906 vehicles/hour during sampling periods. (average = 3177 ± 460). The 7:00 AM - 9:00 PM sampling period had a reasonably constant traffic density during this time period as shown in Figure 2. The figure represents a five day hourly traffic average taken from traffic counts made prior to particulate sampling. The traffic pattern shown in the figure agrees well with data acquired from the city of Philadelphia prior to the study.

SITE LOCATION AND DESCRIPTION

The study was conducted in Northeast Philadelphia at Roosevelt Boulevard between South Hampton and Woodhaven Roads (Figure 3). Roosevelt Boulevard serves as one of the two major north-south traffic arterials for the city. Preliminary meteorological monitoring and review of historical data indicated that winds could be expected to flow across the roadway into the sampling cross-section at least 80% of the days allotted for the study. The sampling cross-sections were located on the grounds of the Pennsylvania State Hospital where the upwind and downwind sites were on open grass covered fields extending more than 1200 meters from the roadway in both the upwind and downwind directions. The sampling site reach was without interfering buildings and service roads for approximately 3500 m along the roadway. The location was within two miles of an EPA Inhalable Particulate (IP) Network Site which averaged 33 $\mu g/m^3$ for IP mass during the period March, 1980 through May, 1981.

SAMPLING SCHEME

Particulate sampling points on the roadway perpendicular were located 220 m upwind, the roadway median, five, 25, 75, 125, and 175 m downwind during Phase I sampling (Figure 4). After 12 sample runs were completed for Phase I, the dichotomous samplers were relocated for vertical, Phase II sampling (Figure 5). Towers were used for elevating the dichotomous samplers to seven and 15 m heights. Samplers were located at 220 m upwind (two m

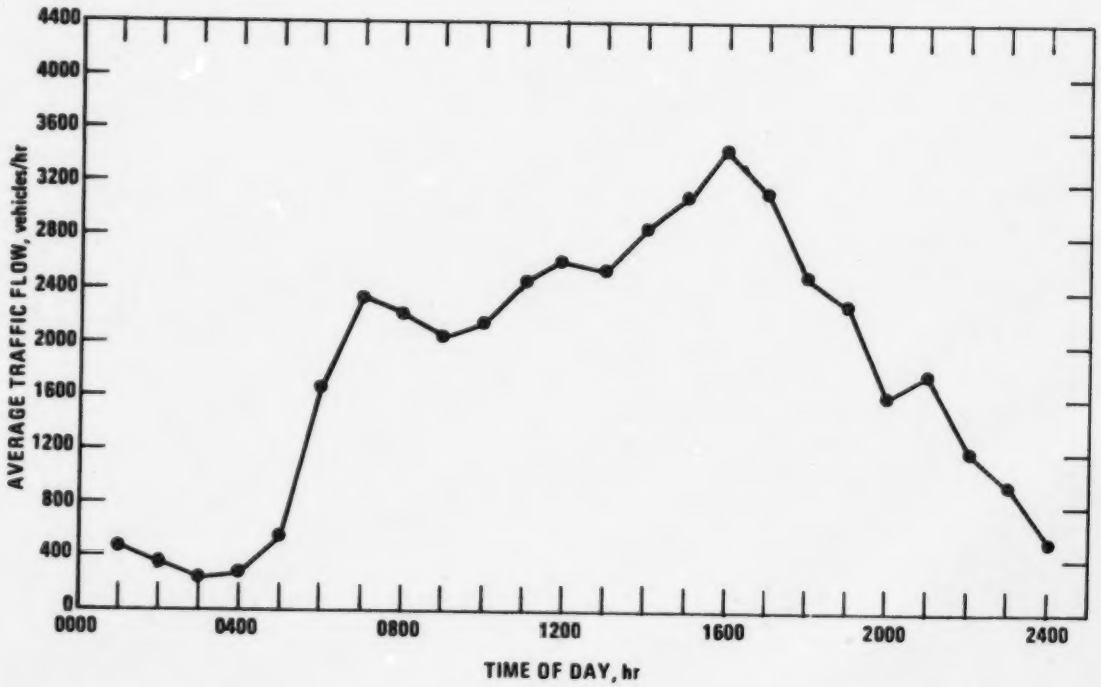


Figure 2. Five-day average hourly traffic flow prior to Philadelphia, PA, roadway study.

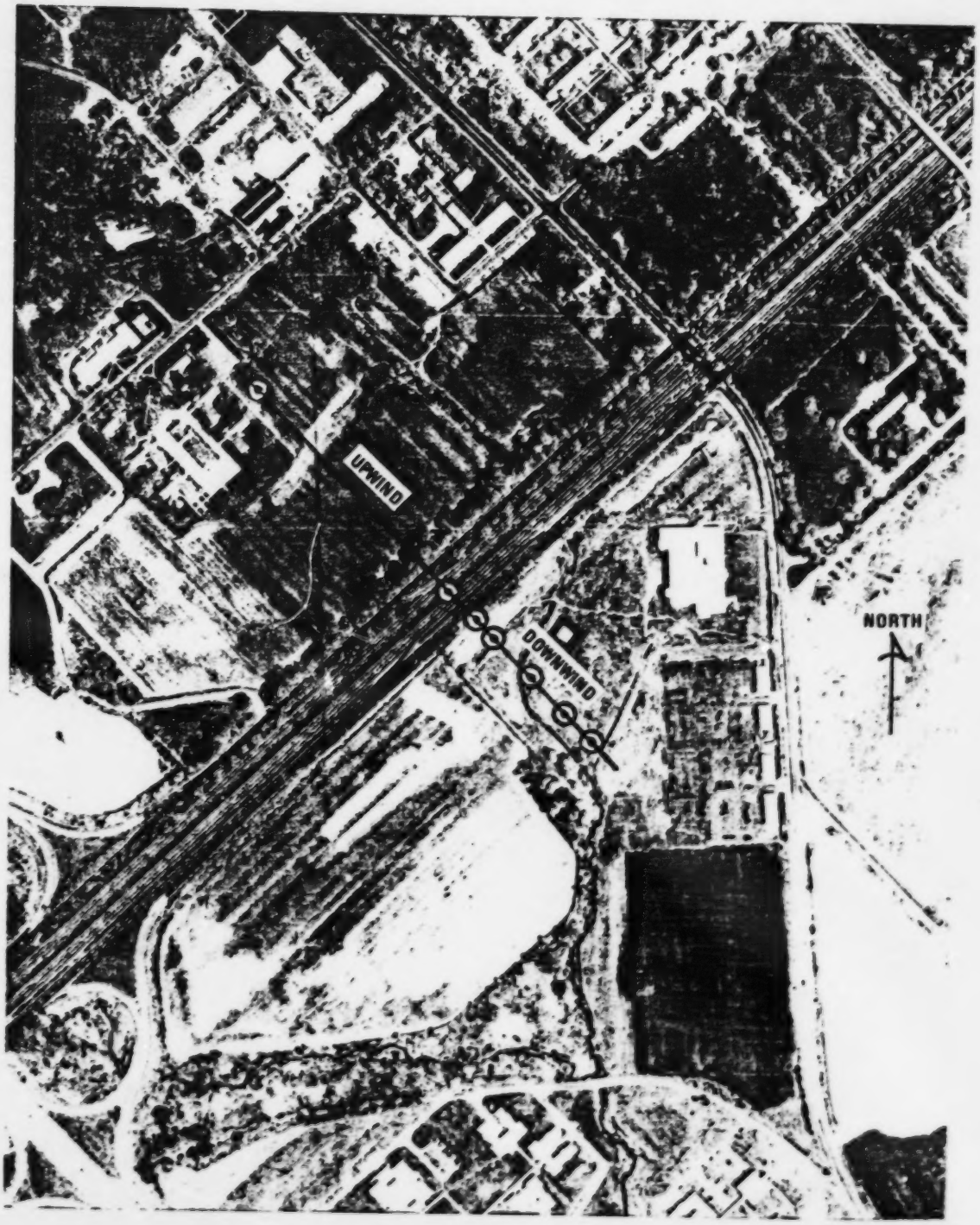


Figure 3. Philadelphia, PA, roadway study site.

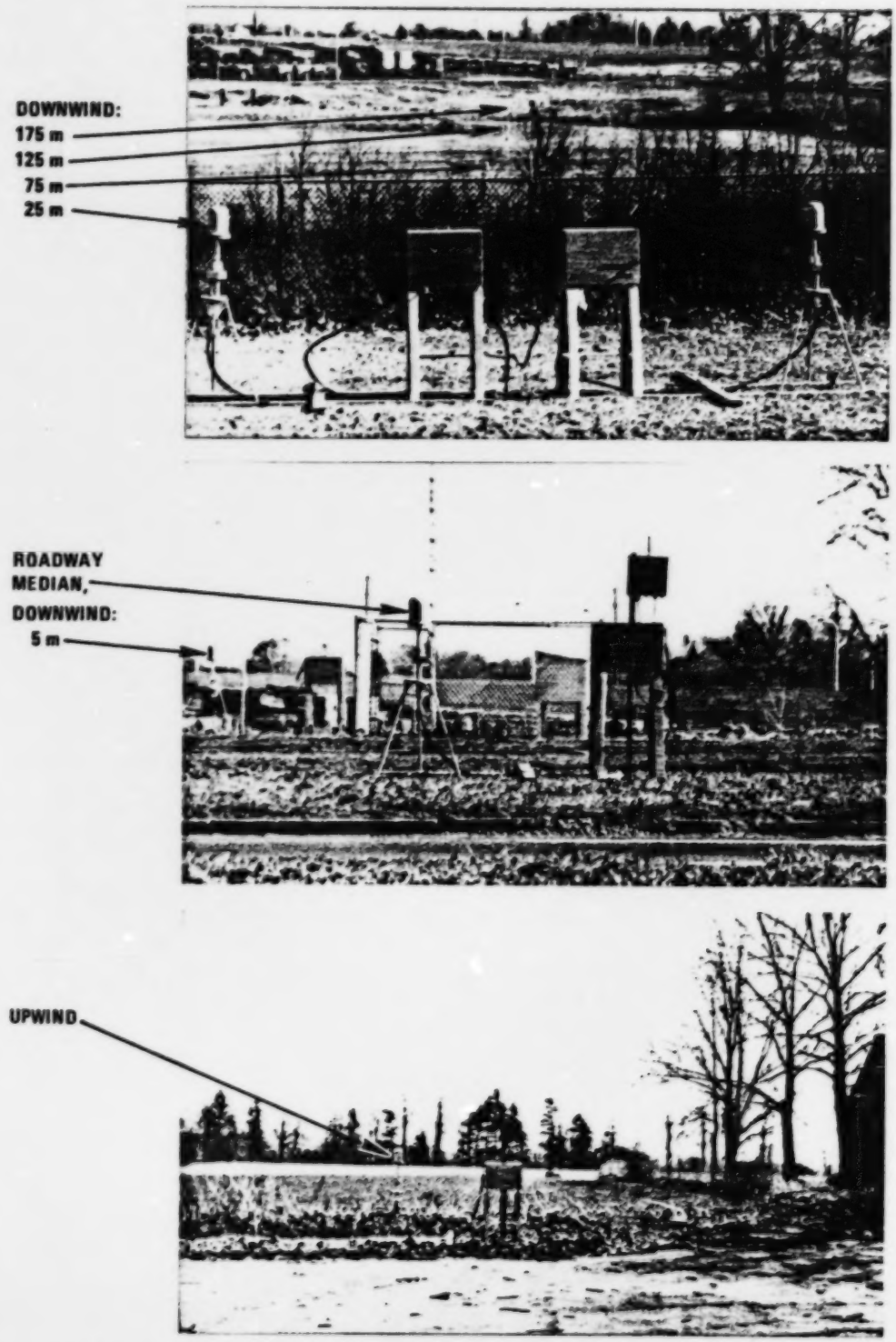


Figure 4. Phase I (2 meter height) sampling sites.

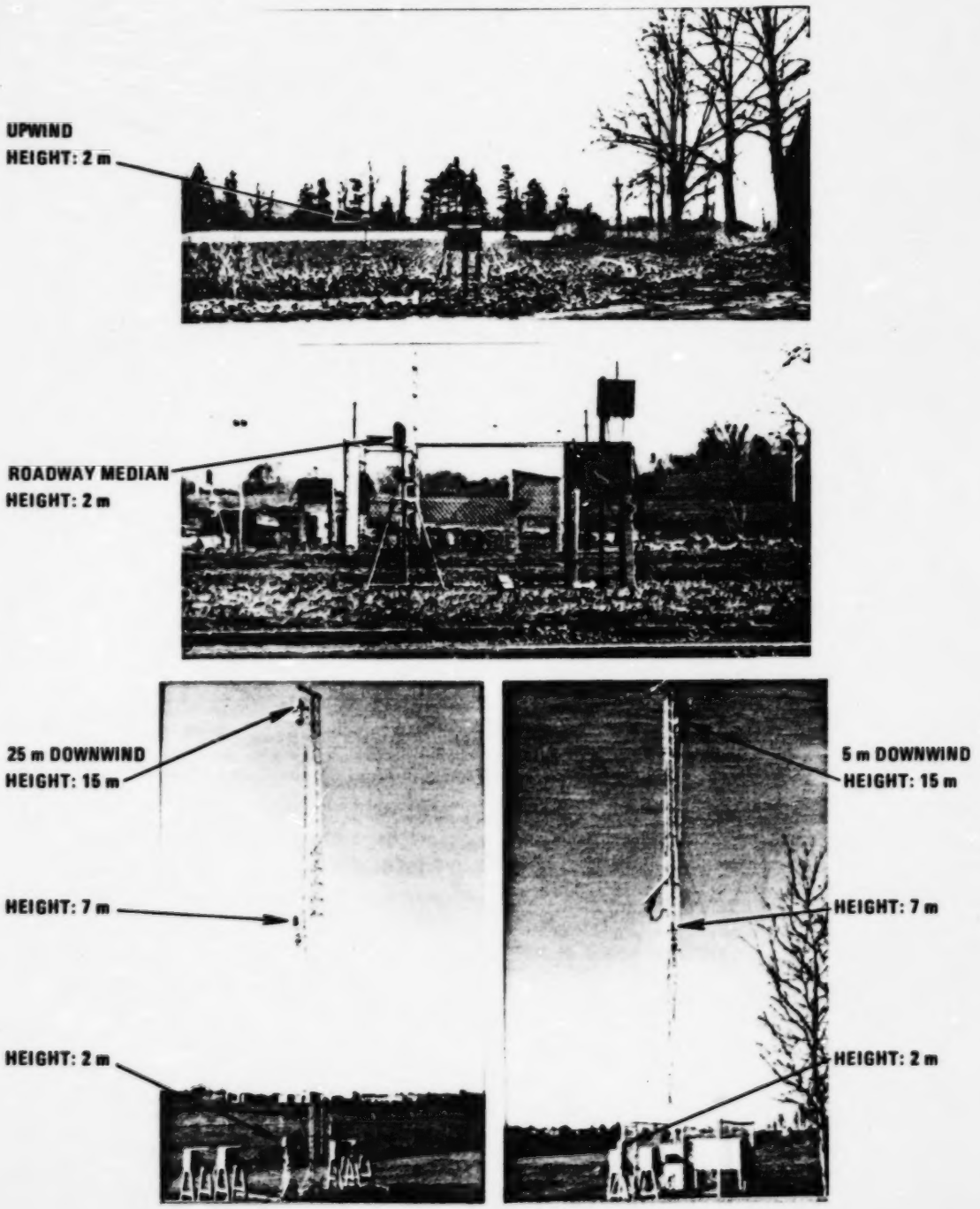


Figure 5. Phase II particle sampling sites.

elevation), the roadway median (two m elevation), five m downwind (two, seven, 15 m elevations), and 25 m (two, seven, 15 m elevations). Sampling was begun simultaneously at each of the seven points located on the roadway perpendicular if the wind speed and direction were within acceptable limits. A collocated sampler at the 25 m downwind, two m height sampling site was operated throughout the study to obtain precision data. Sampler flow checks were made daily, and a performance audit completed to verify that the calibrations had not changed during the study.

SAMPLE ANALYSIS

The dichotomous coarse and fine fraction samples were analyzed gravimetrically for mass concentration. Lead and bromine concentrations were determined by energy dispersive X-Ray Fluorescence. The analysis procedures used for the IP Network, Standard Operating Procedures for the X-Ray Fluorescence Analysis of Multielements on Dichotomous Sample Filters, EMSL-RTP-SOP-EMD-010, November, 1981, were followed.

SECTION 4

RESULTS AND DISCUSSION

Twenty-four sample runs were completed between March 5, 1982 and May 7, 1982 with an average sample time of 10.3 hours. Traffic density, wind speed, and background mass concentrations for each sampling period are summarized in Table 1. Eight horizontal and ten vertical sets of samples (complete at all sampling points) were used for defining the horizontal and vertical particulate mass concentration gradients. In addition, horizontal profiles were obtained on two days immediately following "salting" of the roadway to prevent icing. These data were not included in the general statistical analysis but are described separately.

HORIZONTAL PROFILE

Average downwind concentrations ($\mu g/m^3$) of fine, coarse, and total (coarse + fine) particles for mass and lead mass were examined as a function of distance (m) from the highway. Concentrations measured at ground level (two m height) were averaged over eight days of sampling at each of six downwind and one upwind sites. A plot of the horizontal two m height profile for background and elevated downwind mass is shown in Figure 6. The error bars in the figure represent the standard error of the sample means. The sampling days cover a range of hourly traffic densities from 2160 to 3906 vehicles with wind speeds ranging from 5.8 to 18.5 mph. Based on the concentration measured five m downwind of the roadway edge, the average maximum increases above background (at two m height) in particulate mass and lead concentration downwind of the roadway were:

	Phase I ($\mu g/m^3$)	Phase II ($\mu g/m^3$)
Coarse mass	4.6	8.5
Fine mass	2.6	4.8
Total mass	7.2	13.3
Fine lead	0.47	0.48
Coarse lead	0.08	0.11
Total lead	0.55	0.59
Wind Speed (mph)	11.2	8.4

The coarse particulate mass concentration at the two m elevation increases from the roadway centerline to five meters downwind and then decreases with distance while the fine particulate mass decreases with distance immediately from the centerline. The total mass decreases with distance from the centerline. A significant contribution is made to the coarse fraction from pavement

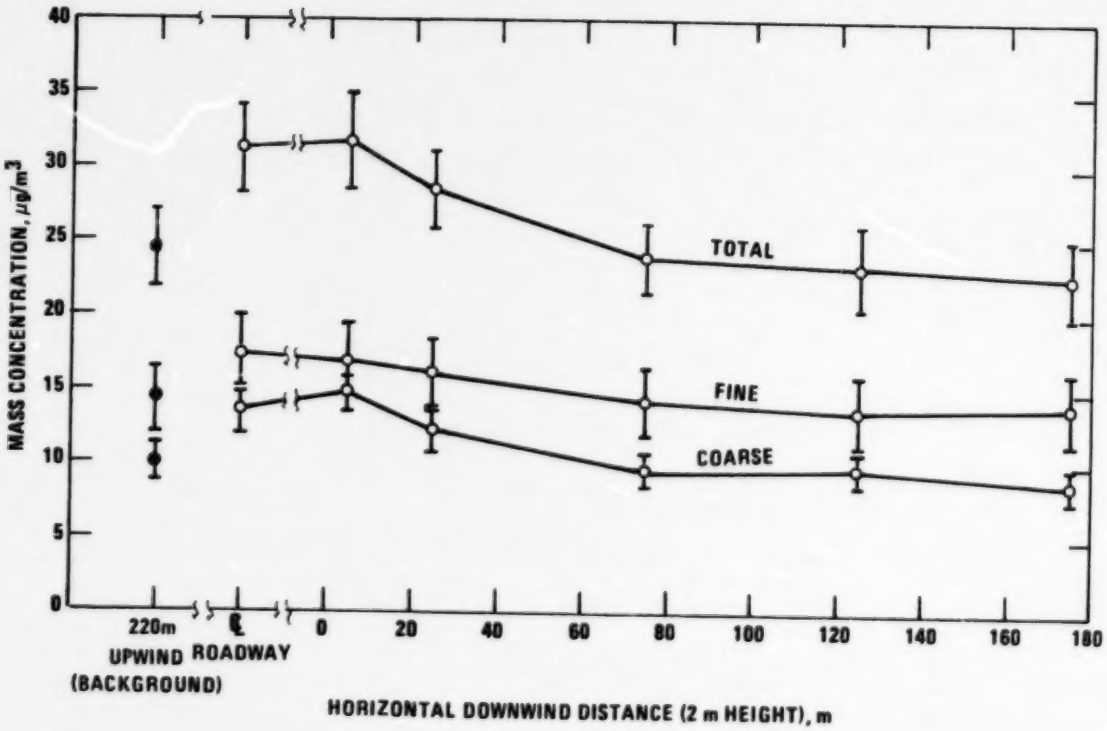


Figure 6. Particulate mass horizontal profile in Philadelphia, PA, roadway study, showing average concentrations and standard error bars.

wear and particle re-entrainment, which contribute little to the fine fraction. This fact and the effect of atmospheric turbulence probably account for the difference in concentration profiles for the different size fractions of the mass.

Logarithmic equations fitted by least squares methods were used to empirically describe (for distances between five m and 175 m downwind of the roadway edge) the relationship between the horizontal two m mass concentration (C) in $\mu g/m^3$ and distance (D) in meters downwind as follows:

Fraction	Equation	Correlation Coefficient	Standard error of estimate ($\mu g/m^3$)
Coarse mass	C= 17.56 - 1.71 ln D	0.990	0.40
Fine mass	C = 18.82 - .99 ln D	0.964	0.53
Total mass	C = 36.378 - 2.71 ln D	0.990	0.66

The coefficients show good correlation of C and ln D. Setting the equations equal to background concentration and solving for distance, the downwind point at which levels reach background were determined. These distances are 74 m (coarse), 87 m (fine), and 77 m (total).

Correlation coefficients between traffic density and mass concentration for each particulate size fraction (fine and coarse) were calculated for each of the six downwind ground level sampling stations (Table 2). Statistically significant correlation at the 90% probability level occurred for fine mass and traffic at five m downwind and at the roadway. No other correlations between particulate mass fractions and traffic density were found at the 90% probability level apparently due to the limited range of traffic densities present during the study. Correlations between wind speed and fine particulate mass (Table 2) were statistically significant at the 90% probability level for all sites. In the case of the coarse fractions none of the sites correlated with wind speed except for the site five m downwind at a height of seven m. Total mass correlated with wind speed at the 90% probability level for all sites except at 175 m downwind.

Lead mass concentration averages also were plotted versus horizontal distance downwind (Figure 7). The error bars in the figure again represent the standard error of the sample means. The lead concentrations decrease with distance from the roadway with the highest concentrations occuring at the center of the roadway (0.17 $\mu g/m^3$ coarse, 0.60 $\mu g/m^3$ fine, and 0.78 $\mu g/m^3$ total). The concentrations for total and fine fractions remain significantly above background for at least 175 m downwind. The lead concentration apparently does not dilute vertically at the same rate as the fine mass mode. Logarithmic equations fit by least squares to empirically describe the deposition and vertical diffusion are given as follows (for distances between five m and 175 m downwind of the roadway edge):

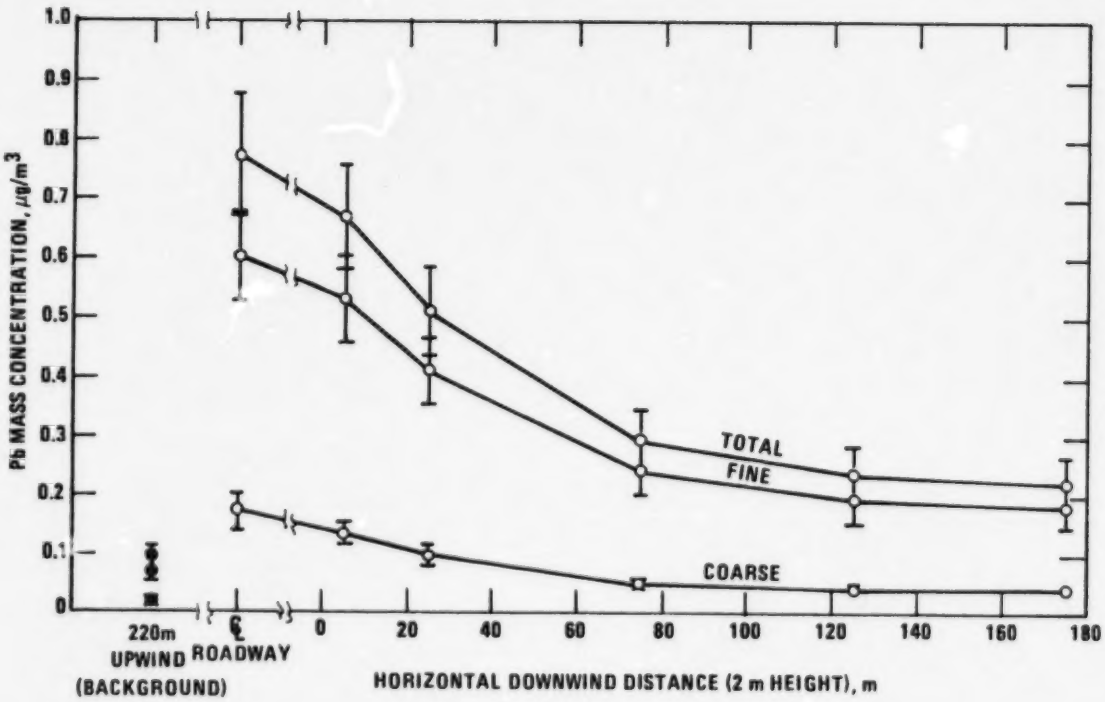


Figure 7. Pb mass horizontal profile in Philadelphia, PA, roadway study, showing average concentrations and standard error bars.

(C = mass concentration, $\mu g/m^3$; D = distance downwind, m)

Fraction	Equation	Correlation Coefficient	Standard error of estimate ($\mu g/m^3$)
Coarse Pb	C = .187 - .029 ln D	0.985	.095
Fine Pb	C = .715 - .106 ln D	0.990	.032
Total Pb	C = .903 - .135 ln D	0.990	.032

The correlation between traffic density and lead concentrations (Table 2) for the fine size fraction were significant at the 90% probability level for all ground level sites except 175 m downwind. Correlations between fine lead and wind speed were found for all sites at the 90% probability level. The correlation between coarse lead and traffic density was significant at the 90% probability level only for sites at five m, 25 m, and 75 m downwind. Coarse lead and wind speed correlations were significant at the 90% probability level at all downwind sites except for five m and 25 m at a height of seven m. Wind speed was a more dominant factor than traffic density in determining both mass and lead concentration levels over the range of conditions encountered.

VERTICAL PROFILE

Vertical profiles for mass and lead in each particle size fraction were first examined by plotting the average concentration for 10 sample runs versus heights of two m, seven m, and 15 m based on measurements from towers located at five m and 25 m downwind. Background measurements were made at the two m height.

Mass concentrations measured at the two tower locations and upwind at a two m height were averaged over 10 days of sampling at each of the six tower locations. A plot of the vertical profiles for mass fractions is shown in Figure 8. The coarse particle concentrations were statistically different from two m background (95% probability level) only at the ground level locations. Fine particulate mass was significantly different from two m background for at least 15 m vertically at the 25 m downwind site and at least seven m vertically at the five m downwind site. Total particulate mass measured at heights above ground level (two m) were found to be significantly different from two m background for only the seven m vertical at the five m downwind location. The vertical gradient mass data was not fit to empirical equations since it was at backround level at some of the elevated measuring points.

Vertical profiles for lead (fine, coarse, and total) are shown in Figure 9. Lead concentrations for fine and total particles were significantly different from background up to 15 m vertically for both downwind towers. Coarse lead was significantly above background for at least seven m vertically at both downwind towers.

No significant correlations were found between composite mass fractions and traffic density at the elevated sites. The same was true for the lead fractions (Table 2). Wind speed correlated with fine mass at the 99% probability level for all sites except the five m downwind, 15 m height site. Coarse particle mass fractions correlated significantly with wind only at the five

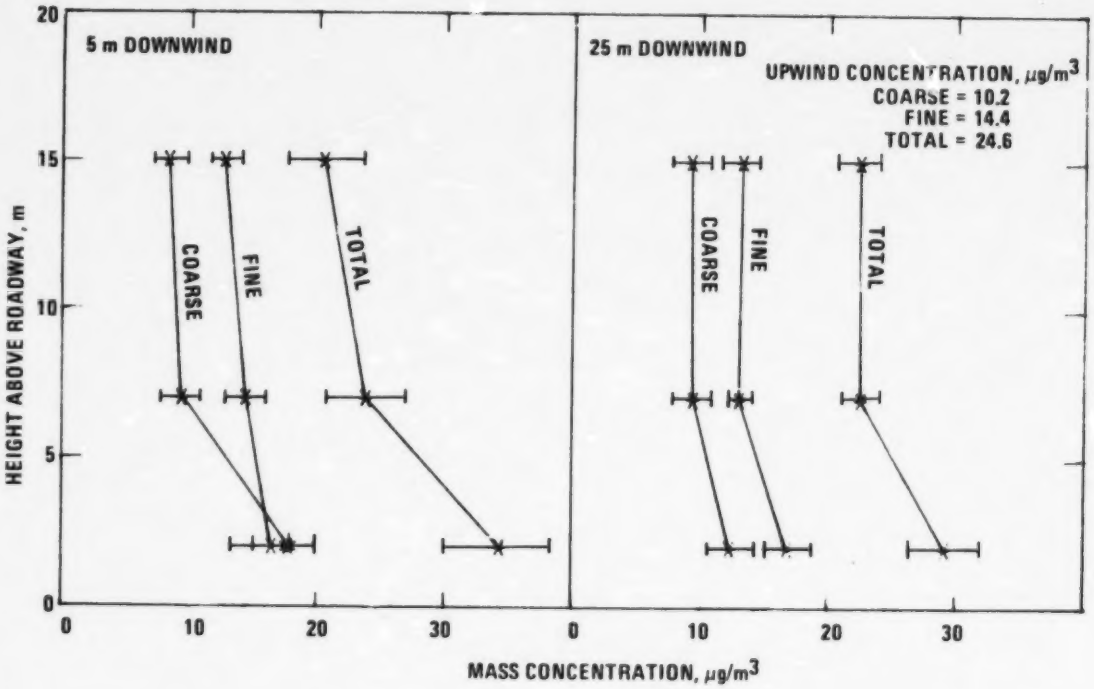


Figure 8. Vertical profile of downwind mass concentration in Philadelphia, PA, roadway study, showing average concentrations and standard error bars.

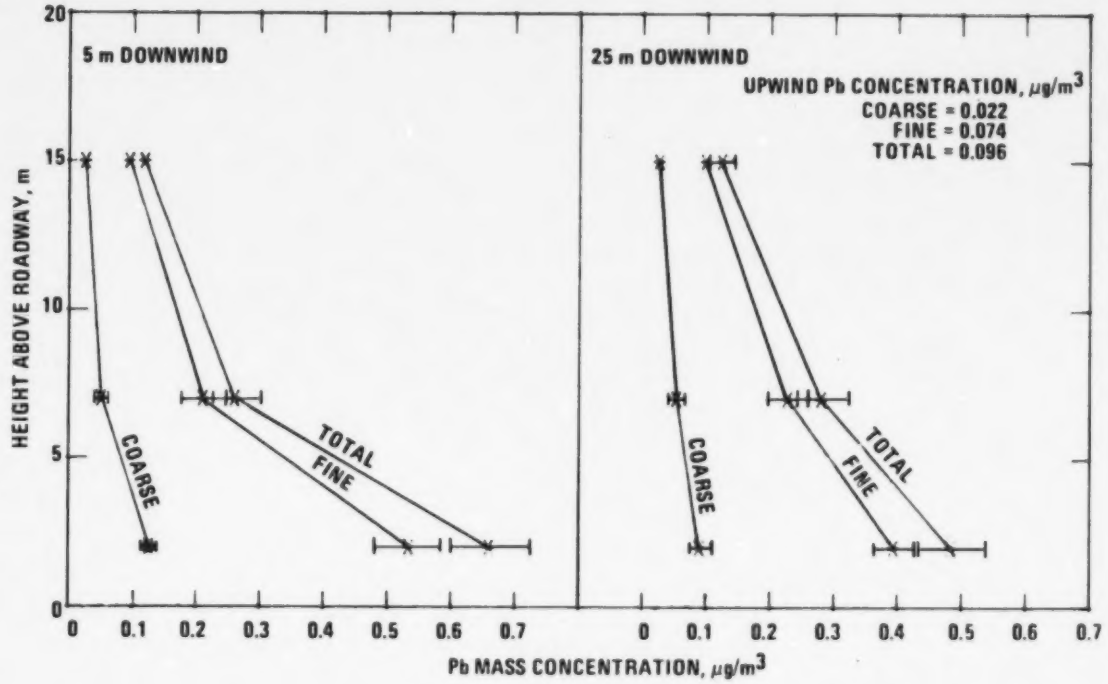


Figure 9. Downwind Pb mass vertical profile in Philadelphia, PA, roadway study, showing average concentrations and standard error bars.

and 25 m downwind sites at the seven m height. Coarse lead fractions correlated significantly only at the 15 m height at five m and 25 m downwind (Table 2). Fine lead showed a significant correlation with wind speed at all sites.

Since fine and total lead concentrations were above background up to a 15 m height, logarithmic equations as follows, were fitted by least squares to empirically describe the vertical dilution, (C = mass concentration, $\mu g/m^3$; H = distance above ground, meters):

Fraction	Equation	Correlation Coefficient	Standard error of estimate $\mu g/m^3$
Fine lead (5m dw)	C = 0.674 - 0.222 ln H	0.990	0.030
Total lead (5m dw)	C = 0.833 - 0.273 ln H	0.990	0.057
Fine lead (25m dw)	C = 0.498 - 0.145 ln H	0.998	0.013
Total lead (25m dw)	C = 0.609 - 0.177 ln H	0.998	0.008

BROMINE/LEAD RATIOS

The Br/Pb ratios found to exist in the downwind roadway particulate matter were consistent with ratios reported in the literature.[5,6] As described by Harrison and Sturges, the major particulate species of exhaust lead and bromine in the United States is PbBrCl and should give a Br/Pb mass ratio of 0.386 in the exhaust. The average Br/Pb ratio for all ten downwind monitoring locations was 0.36 ± .06 in the fine fraction and 0.55 ± .26 in the coarse fraction. Eighty percent of the lead mass was found in the fine fraction.

DEVELOPMENT OF EMPIRICAL MODEL FOR ROADWAY GENERATED PARTICULATE LEVELS

Rodes and Holland developed an expression in the Los Angeles Catalyst Study[1] which predicts (for two m height) the exponential horizontal decrease of an initial concentration of an inert gas measured at a given point downwind of the centerline of a roadway. This approach was used to develop an equation for computing particulate and lead mass concentration at heights up to 15 m above ground level and distances between five m and 175 m downwind of roadway edge for cross-wind cases at wind speeds between three and six mph. Rodes and Holland's equation is

$$C = C_{26} \left(\frac{26}{X}\right)^{B_1} + C_b$$

Where C = mass conc. at distance downwind ($\mu g/m^3$)
C_{26} = mass conc. at initial point downwind 26 m from roadway centerline ($\mu g/m^3$)
B_1 = "vertical" dilution parameter
X^1 = distance downwind from centerline (m) where 26M<X<414m
C_b = background conc. ($\mu g/m^3$).

It was modified to account for the vertical gradient. The term $(2/H)^{B_2}$, which describes the vertical gradient at a given height H from the initial height of two meters is added to the Rodes equation to give:

$$C = C_{31} \left(\frac{31}{D}\right)^{B_1} \times \left(\frac{2}{H}\right)^{B_2} + C_b$$

Where C_{31} = mass conc. at initial five m downwind point, 31 m from centerline of road and two m above ground ($\mu g/m^3$)
D = distance downwind from centerline (m) where 31M<D<206M
B_1 = horizontal gradient coefficient
H^1 = vertical height (m) where 2M<H<15M
B_2 = vertical gradient coefficient
C_b^2 = background upwind concentration ($\mu g/m^3$).

At any downwind two m sampling height, the third term becomes unity [$(2/2)^{B_2} = 1$] and the equation reduces to the same form as Rodes and Holland equation. Least square regressions were used to determine the value of B_1 and B_2 based on measurements made during the study. Data acquired from the horizontal and vertical downwind mass and lead measurements (above background) were combined to determine siting constraints in both the horizontal and vertical direction. Average wind speed and traffic density of 11.0 mph and 3304 veh/hr during horizontal profiling compared to an average of 9.4 mph and 3129 veh/hr during vertical profiling providing similar mass loading, mixing and resulting downwind mass concentrations for the two sampling configurations (Phase I and Phase II).

Results of the regressions are as follows:

(a) Total Mass (<15 microns)

$$\text{Conc } (\mu g/m^3) = 15.91\left(\frac{31}{D}\right)^{1.28}\left(\frac{2}{H}\right)^{1.67} + C_b;\ R^2 = .83$$

(b) Coarse Mass (2.5-15 microns)

$$\text{Conc } (\mu g/m^3) = 11.09\left(\frac{31}{D}\right)^{1.99}\left(\frac{2}{H}\right)^{2.24} + C_b;\ R^2 = .88$$

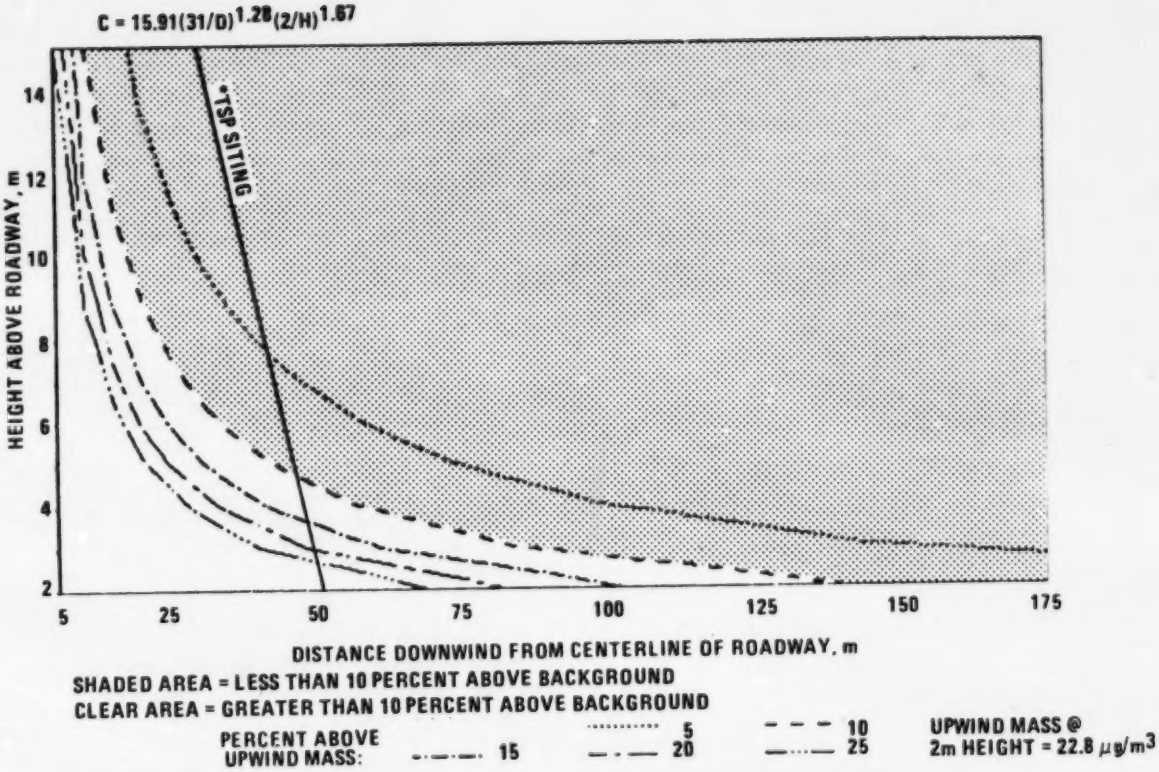
(c) Fine Mass (0-2.5 microns)

$$\text{Conc } (\mu g/m^3) = 4.56\left(\frac{31}{D}\right)^{.82}\left(\frac{2}{H}\right)^{.35} + C_b;\ R^2 = .67$$

(d) Fine Lead (0-2.5 microns)

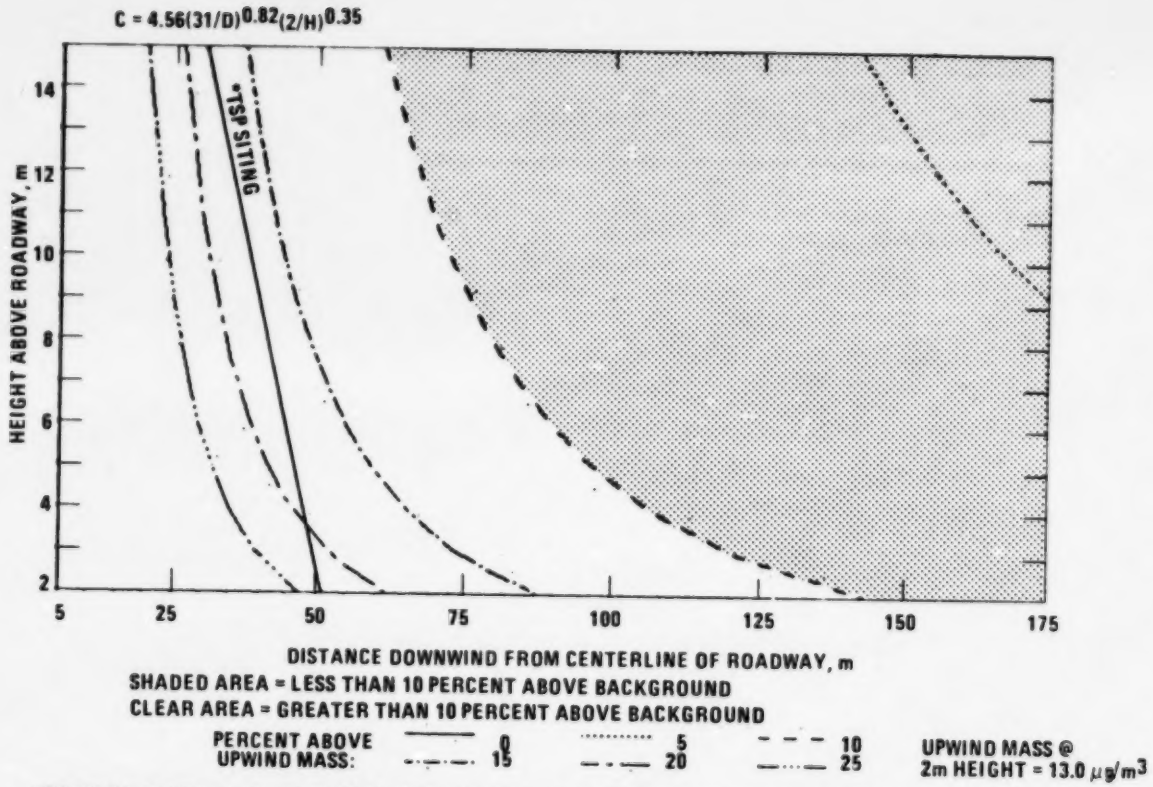
$$\text{Conc } (\mu g/m^3) = .46\left(\frac{31}{D}\right)^{1.24}\left(\frac{2}{H}\right)^{1.50} + C_b;\ R^2 = .96$$

These equations, based on the average of site differences between upwind and downwind concentration levels, were used to construct contour maps (figures 10a, 10b, and 10c respectively for total, fine, and coarse mass, figure 11 for fine lead). Isolines describe percentages of mass (above background) at given heights and distances downwind of the roadway. The isopleths and empirical formulas are not intended to represent a general model for describing mass concentration decay of particulate mass around all roadways but do provide an adequate empirical description under traffic and wind conditions present during the study. They represent only perpendicular (±45°) crosswind conditions. The vertical component of the regression is based on measurements from only the two towers. Since the downwind plume is rising with downwind



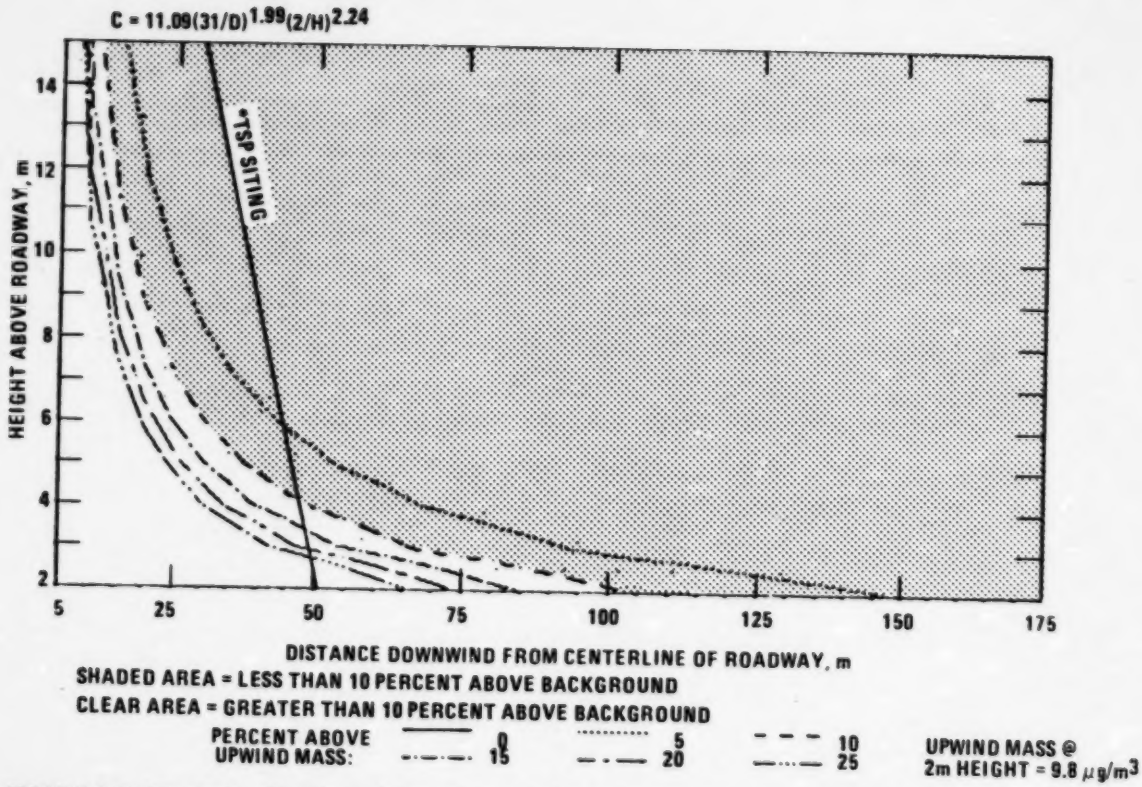
*FROM: F.R.M., VOL. 44, No. 92, MAY 10, 1979, "ACCEPTABLE ZONE FOR SITING TSP MONITORS".

Figure 10a. Regions of excess Total Inhalable Particulate (<15 μm) near roadways (see text for explanation).



*FROM F.R.M. VOL 44, No. 92, MAY 10, 1979, "ACCEPTABLE ZONE FOR SITING TSP MONITORS".

Figure 10b. Regions of excess fine particulate (0 - 2.5 μm) near roadways (see text for explanation).



*FROM F.R.M. VOL. 44, No. 92, MAY 10, 1979 "ACCEPTABLE ZONE FOR SITING TSP MONITORS".

Figure 10c. Regions of excess coarse particulate (2.5 - 15 μm) near roadways (see text for explanation).

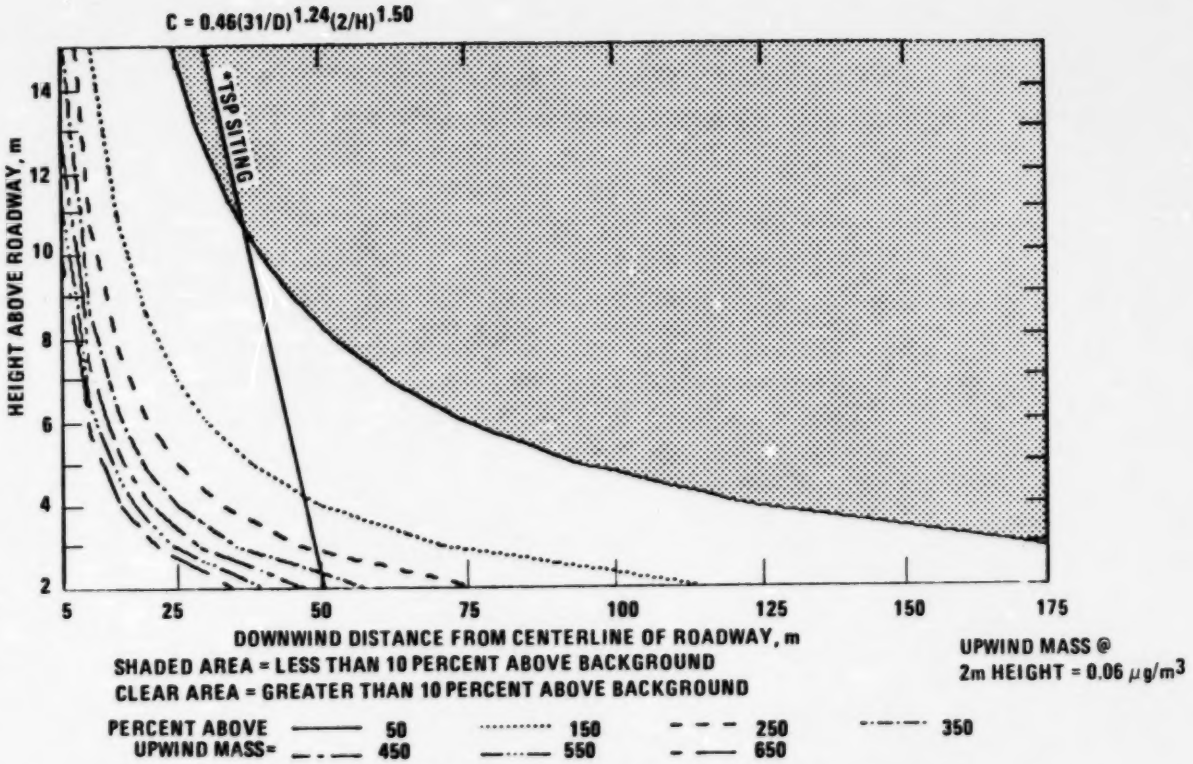


Figure 11. Regions of excess fine particulate lead (0 - 2.5 μm) near roadways (see text for explanation).

distance, the model should be considered only as an estimate. Ideally, at least three tower locations are needed since the plume rise is exponential with respect to distance downwind.

As shown in the graphs, the fine and coarse mass fractions exhibit contrasting patterns downwind of the roadway. At two m height, a 25% above background mass level extends downwind from roadway centerline 47 m for fine and 65 m for coarse.

Figure 11 for fine lead shows a distance of 75 m downwind is required for the concentration to drop to 250% above background at the two m height. Above the six m height, lead concentration falls very rapidly with height (the 250% level at 15 m height = eight m downwind). The isopleths show the majority of coarse mass and fine lead to be concentrated below the six m height, while the fine mass is more evenly distributed throughout the two-15 m vertical. This can be explained by the fact that above background fine lead was elevated ∿ 800% and coarse mass ∿ 45% in comparison to only ∿ 18% for fine mass, making fine mass downwind more equally distributed in the vertical. These statistical models are not valid for distances less than five m of the roadway edge.

Applying the Federal Register Criteria for TSP siting constriction (noted on figures), the following observations are made:

A. IP (<15 μm) mass is 37% above background at the two m height TSP allowable point, six % at seven m height and two % at 15 m height.

B. Fine mass (0-2.5 μm) is 23% above background at the two m height TSP allowable point, 17% at seven m height and 17% at 15 m height.

C. Coarse mass (2.5-15 μm) is 42% above background at the two m height TSP allowable point, three % at seven m height and one % at 15 m height.

D. Fine lead (0-2.5 μm) is 413% above background at the two m height TSP allowable point.

SPECIAL OBSERVATIONS AND ANALYSES

Effect of Road Salting

On March 7, after several inches of snow had fallen, salt was added to the roadway. The samples collected on the following day showed extremely elevated coarse mass downwind of the roadway. On March 9, the coarse mass was still above the average measured during the study even though it had decreased considerably from the previous day. Figure 12a shows the two m horizontal profile of coarse mass measured on the two consecutive days after salting (approximately 100 $\mu g/m^3$ peak) and compares them to the mean of Phase I sampling. The third day of sampling after road salting found coarse mass diminished to average level. Figure 12b demonstrates the lack of salting influence on the fine mass. No significant rise in the fine fraction occurred on the days immediately following road salting. March 8th and 9th fine fraction levels were consistent with the study mean as shown in plots of two

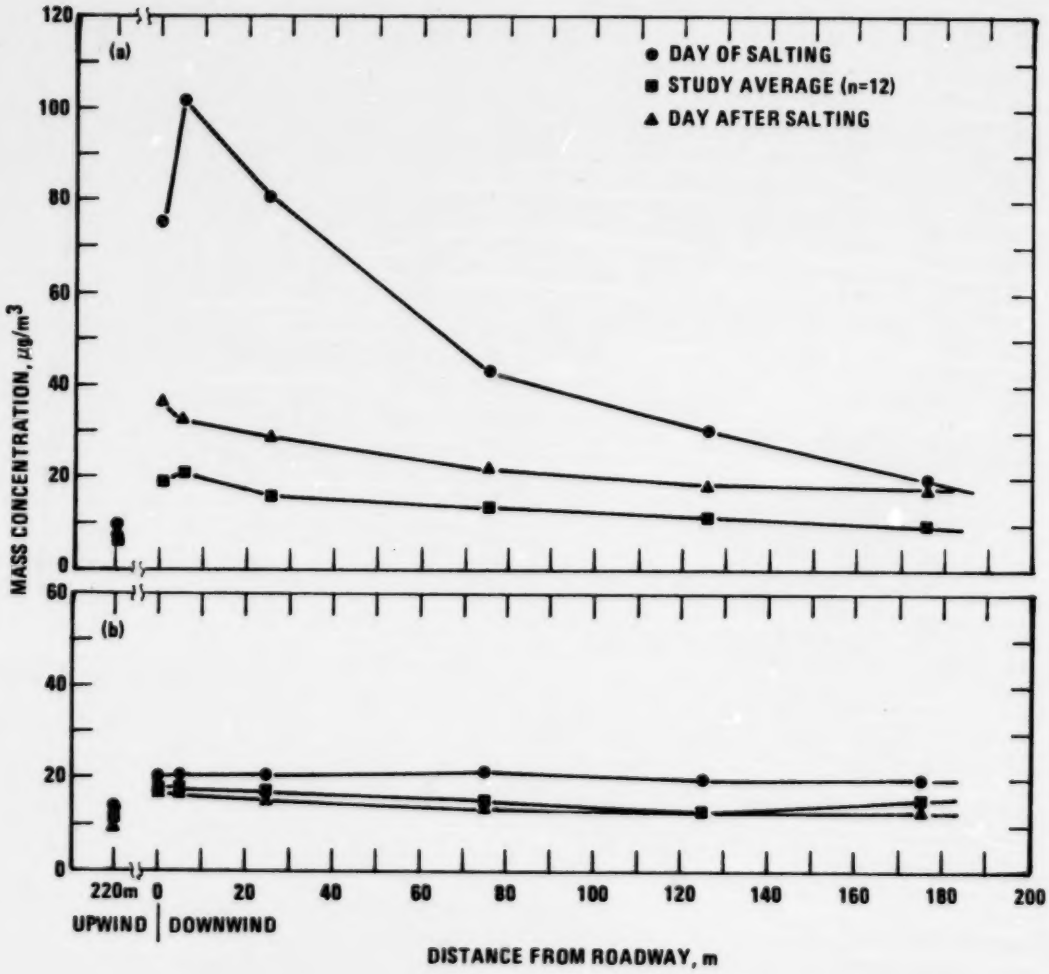


Figure 12. Effect of road salting on (a) coarse (2.5-15 μm), and (b) fine (0-2.5 μm) particulate mass concentration in Philadelphia, PA, roadway study, March 8 and 9, 1982.

m fine mass, Figure 12b. Large cities in northern climates where snow occurs could very well have elevated TSP averages due to sampling on days when salt is present on the roadways.

Effect of Wind Speed on Particulate Mass Concentrations

Even though good correlations were not obtained between mass and wind speeds, it was obvious that the wind speed was definately affecting mass levels. The horizontal two m measurements were divided into two groups (wind speeds >11.0 mph; wind speeds <11.0 mph), and the average mass concentration of each group was plotted for fine and coarse fractions at all sampling sites. Traffic densities for the two groups of measurements averaged 3420 vehicle/hour and 3000 vehicle/hour respectively, giving similar mass loadings. As shown in Figure 13a, differences in fine mass for the two wind speed ranges is significant with background fine mass dropping from 19.5 $\mu g/m^3$ to 6.5 $\mu g/m^3$ when the wind speed range increases from (5.8-10.6 mph) to (13.0-17.8 mph).

Coarse fraction mass difference for the two wind ranges is smaller than for fines, dropping from 9.5 $\mu g/m^3$ at wind speeds between 5.8 and 10.6 mph to 4.2 $\mu g/m^3$ for wind speeds between 13 and 13.1 mph (Figure 13b). The 17.3 mph measurements were omitted for coarse particles since re-entrainment became significant at that speed. As seen from both figures 13a and 13b, both background and downwind concentrations (fine and coarse modes) were similarly affected by changing wind speeds. It appears that wind speeds are much more influential on mass levels than vehicle densities between 2119 and 3906 vehicle/hour.

Measured vs. Computed Lead Concentrations

A number of comprehensive laboratory studies have characterized the percent lead content in auto particulate emissions. These emissions have been shown to vary widely in both amounts and composition as driving conditions change. For catalyst equipped cars using low-lead gasoline, only traces of lead are emitted; while for non-catalyst cars lead compounds represent as much as one-third of the total particulate emissions[7]. Using laboratory data associated with driving conditions similar to those found on Roosevelt Boulevard (45 mph cruise), an estimate of the fine and coarse lead ambient concentrations can be computed from the particulate mass measurements. Assuming 79% for the portion of lead emissions that are contained in the fine fraction mass[7], a vehicle mix of 40% leaded and 60% non-leaded[8], engine related emissions of 80% fine and 20% coarse[7], tire and brake 100% coarse[7], Roadway Study fine mass 100% engine related[7], and (6) Roadway study coarse mass 20% engine related plus 28% vehicle related[9], fine lead mass concentration can be computed as follows:

$$\text{Fine lead concentration} = \text{total particulate mass} \times \%\ \text{catalyst autos} \times \text{fine lead/total lead} \times \text{lead composition factor} = \underline{0.41}\ \mu g/m^3$$

The 0.41 $\mu g/m^3$ of lead computed compares to 0.53 $\mu g/m^3$ measured. The coarse lead concentration level can be computed in the same manner considering both engine related and other vehicle related emissions. Coarse

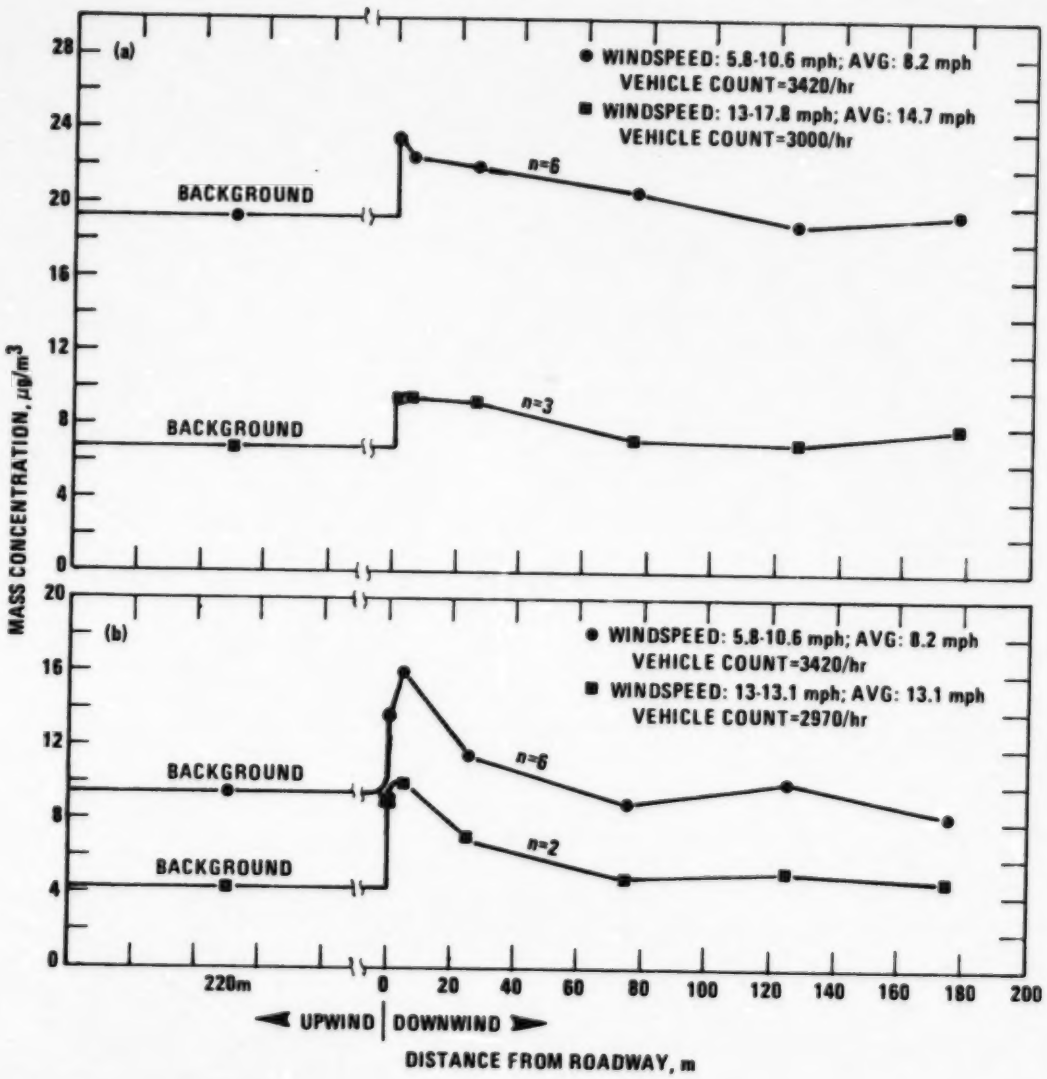


Figure 13. Effect of windspeed on (a) fine (0-2.5 μm) and (b) coarse (2.5-15 μm) particulate mass concentration in Philadelphia, PA, roadway study.

lead concentrations were computed as 0.13 $\mu g/m^3$ and compares to 0.15 $\mu g/m^3$ measured. Roadway mass measurements showed 78% of lead to be in the fine fraction. That compares favorably to the 79% established from laboratory experiments.[7]

QUALITY ASSURANCE RESULTS

Field operations were performed in accordance with the EMD approved protocol[10] and the QA project plan.[11] The rate of data capture was better than 95%.

The coefficients of variation for collocated dichotomous samplers at the 25 m site were as follows:

	Mass	Pb	Br
Fine	13%	15%	9%
Coarse	22%	55%	30%

The coefficients of variation for fine and coarse mass measurements compare favorably with the reproducibilities of 13% for the fine and 18% for the coarse fractions of dichotomous samplers reported in an earlier paper evaluating IP samplers[12].

An independent quality assurance performance audit by the Research Triangle Institute was performed on March 23, 1982. Sampler flow rate audit results were as follows:

Sampler Location	% Difference[a] Total	Coarse
Upwind	0.0	- 7.2
Median	+0.6	- 5.1
5 m dw	+2.5	+ 1.8
25 m dw (Regular)	+5.0	+ 3.7
25 m dw (Collocated)	-2.9	- 1.8
75 m dw	+4.4	+12.8
125 m dw	+3.1	+ 1.8
175 m dw	-0.6	- 1.8
MEAN	+1.5%	+ 0.5%

[a] (audit-actual)/(audit+actual)/2 X 100

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TABLE 1: SUMMARY OF TRAFFIC DENSITY, WIND SPEED, AND BACKGROUND INHALABLE PARTICULATE MASS CONCENTRATIONS DURING SAMPLING

Sample Number	Date of Sample	Average Traffic Density (vehicles/hour)	Average Wind Speed (mph)	Average Background IP Mass Conc. ($\mu g/m^3$)
1	3/5/82	3550	9.2	38.2
2	3/8/82	3782	10.5	17.4
3	3/9/82	3669	9.3	17.4
4	3/11/82	3783	8.2	31.7
5	3/19/82	3906	8.4	30.6
6	3/20/82	2780	10.6	23.7
7	3/23/82	3006	5.8	31.4
8	3/26/82	3177	13.3	12.6
9	3/27/82	2767	12.9	10.4
10	4/1/82	3046	17.8	21.0
11	4/2/82	3497	7.1	16.7
12	4/4/82	2160	18.5	19.1
13	4/10/82	2999	9.1	24.2
14	4/11/82	2119	8.7	19.9
15	4/12/82	3602	8.5	18.8
16	4/14/82	3094	8.3	19.9
17	4/18/82	3037	13.0	8.3
18	4/21/82	3074	10.8	21.3
19	4/22/82	3385	12.1	25.8
20	4/23/82	3225	11.6	28.8
21	4/29/82	2707	4.6	23.3
22	4/30/82	3436	7.4	25.0
23	5/3/82	3211	7.2	29.7
24	5/7/82	3232	6.5	19.0

TABLE 2: CORRELATION OF PARTICULATE MASS AND LEAD CONCENTRATIONS WITH TRAFFIC AND WIND SPEED

A. Mass

		Fine Mass		Coarse Mass	
Site	Location	Traffic Density	Wind Speed	Traffic Density	Wind Speed
601	Upwind	.15	-.49	-.16	.34
602	Roadway Center	.62*	-.84**	.05	-.05
603	5 m dw[a], 2 m h[b]	.61*	-.84**	-.07	-.17
604	25 m dw, 2 m h	.61	-.82*	.04	.41
605	75 m dw, 2 m h	.62	-.85**	-.20	.38
606	125 m dw, 2 m h	.60	-.78**	-.30	-.15
607	175 m dw, 2 m h	.56	-.79**	.08	.29
611	5 m dw, 7 m h	-.11	-.75**	.49	-.63**
612	5 m dw, 15 m h	.14	-.41	.45	-.12
614	25 m dw, 7 m h	-.04	-.82**	.45	-.48
615	25 m dw, 15 m h	-.22	-.81**	.32	-.31

B. Lead

		Fine		Coarse	
Site	Location	Traffic Density	Wind Speed	Traffic Density	Wind Speed
601	Upwind	.45	-.65*	.28	-.46
602	Roadway Center	.81**	-.94**	.52	-.78**
603	5 m dw, 2 m h	.84**	-.94**	.77**	-.85**
604	25 m dw, 2 m h	.85**	-.88**	.75**	-.76**
605	75 m dw, 2 m h	.68*	-.83**	.68*	-.70**
606	125 m dw, 2 m h	.69*	-.83**	.55	-.79**
607	175 m dw, 2 m h	.57	-.86**	.52	-.66*
611	5 m dw, 7 m h	.03	-.76**	.38	-.52
612	5 m dw, 15 m h	.28	-.68**	-.19	-.88**
614	25 m dw, 7 m h	.41	-.78**	.37	-.45
615	25 m dw, 15 m h	.24	-.69**	-.23	-.73**

[a] = downwind

[b] = height

*significantly different from zero at the 90% probability level

**significantly different from zero at the 95% probability level